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TECHNICAL REPORT NUMBER 3

Contract Nonr 248 (09)

"A STUDY OF FUNDAMENTAL PROCESSES CAUSING INSTABILITY IN D-C ARCS"

In the employment of d-c arcs for welding and in arc furnaces for melting of metals one of the prime considerations is the stability of the arc. The design of the furnace or the execution of the welding process is limited by the control processes necessary to maintain satisfactory stability. From a practical standpoint stability means the constancy of heat input at the place desired in the welding or melting process in which the arc is being used. From an electrical standpoint the stability is manifested by the constancy of current and voltage input to the arc.

It is well known that an oscillogram of the voltage from a d-c welding arc shows rapid variations in voltage, usually of random frequency and magnitude. If the variations become too excessive the arc will get out of control and either be extinguished or do an unsatisfactory job of welding. In any case the performance and utility are greatly enhanced if the variations or "oscillations" in current and voltage can be reduced or eliminated. To achieve this goal there must be obtained a knowledge of the basic causes of the oscillations and it was the purpose of the work reported here to ascertain this.

Accordingly, apparatus was set up to make simultaneous measurements of the oscillations of current, voltage, light and sound in the d-c arc and to correlate the results with those controllable parameters which might lead to a better understanding of the fundamental processes involved. By means of a dual beam oscilloscope it was possible to make a direct comparison of any two of the above types of oscillations.

It was found that the oscillations were of two types (1) high frequency, high amplitude oscillations occurring at currents above about 15 amperes and

(2) low frequency, low amplitude oscillations of a very uniform nature occurring at currents below 15 amperes. Results obtained from our studies of the high frequency oscillations were described in the paper "The Hissing Arc and Radio Frequency Self-Generated Oscillations in the D-C Carbon Arc" by B. H. List and T. B. Jones which was presented at the American Institute of Electrical Engineers Third Conference on Electric Welding at Detroit, Michigan, April 16-18, 1952. The paper was subsequently published by the AIEE in their Publication S-46 Electric Arc and Resistance Welding-III, p. 209-218, October, 1952. It was also published by the AIEE in Electrical Engineering, Vol. 72, No. 8, p. 683-690, August, 1953. Reprints of this paper were included in Technical Report Number 2 - "The Electrical Stability Of High Current Arcs In Air And In Controlled Gaseous Mixtures", December, 1952.

Results of the studies of the low frequency oscillations were described in the paper "Low-Frequency Self-Generated Oscillations in the D-C Carbon Arc" by B. H. List and T. B. Jones. This paper was presented at the 1953 Winter General Meeting of the American Institute of Electrical Engineers and was published by the AIEE in Electrical Engineering Vol. 72, No. 7, July, 1953, p. 612-619. A reprint of this publication is attached hereto and made a part of this report.

The principal conclusions from the low frequency studies are as follows:

1. A Study of the d-c arc in air at normal temperatures and pressures between solid carbon electrodes has disclosed the presence of symmetrical, uniform oscillations of current, voltage, light, and sound occurring at current values just below the hissing stage.

2. The oscillations are of low frequency in the range 50 to 400 cycles.

3. The oscillations occur with high uniformity only after the anode tip has attained its characteristic shape.

4. The frequency of the oscillations is affected by the material, diameter, and separation of the electrodes and by the arc current, but not by reactance present in the power supply.

5. The oscillations are caused by rotation of the anode spot about the periphery of the anode due to the presence of an unsymmetrical magnetic field caused by the arc current itself at the anode surface.

6. An empirical equation has been developed to express the frequency of the oscillations as a function of current and electrode parameters.

7. It is believed that the behavior of the anode spot and the influence of the arc's own magnetic field as reported here have a direct bearing on the initiation of the "hissing" arc and on its characteristics.

It is seen that the basic cause of both the low frequency and high frequency oscillations is motion of the anode spot across the surface of the anode due to the arcs own magnetic field in combination with the natural configuration of the electrode face. This process is inherent in the arc itself and is in no way concerned with the external electrical circuit supplying power to the arc. It is not proposed that this is the only cause of instability in the d-c arc but it is believed to be one of the more important and basic sources of oscillations. This work has therefore isolated one prime source of instability and "pinpointed" it to the anode spot as affected by the arcs own magnetic field. This contribution to the fundamental knowledge of the arc should be of assistance to those who are seeking to improve its stability in its many applications.

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Low-Frequency Self-Generated Oscillations in the D-C Carbon Arc

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A study of the fundamental properties of the d-c arc was undertaken starting with very low currents of 1 ampere or less and gradually increasing the current. Simultaneous observations of the variations in voltage, current, light, and sound produced by the arc were correlated with those controllable parameters in an attempt to understand better the basic processes involved.

UNDER THE sponsorship of the Office of Naval Research, the Department of Electrical Engineering of Johns Hopkins University has been conducting a study of the fundamental properties of the d-c arc. Particular attention has been given to arcs of higher current values (10 to 200 amperes) at atmospheric pressure, such as occur in welding, searchlights, circuit breakers, and so forth.

It long has been known that the voltage across such arcs is not always a steady d-c value. In many cases, particularly in welding operations, it is subject to wide random variations even though the voltage of the source supplying power to the arc remains perfectly steady. In the case of the carbon arc, the familiar "hissing arc" has been the subject of wide controversy and its mechanism is still in doubt.

In view of the importance of this behavior on the stability and utility of the arc, it was felt that a careful investigation of its nature was warranted. It was felt, also, that an understanding of the variations might lead to a better understanding of the basic arc processes for all types of arcs.

PLAN OF THE RESEARCH

THE PRIMARY PORTION of the study was devoted to the carbon arc, since variations in voltage and current occasioned by material transfer, such as occur in metallic arcs, would not be present with carbon electrodes. A search of the literature disclosed that one of the first thorough studies of the carbon arc was made by Ayrton[1] before 1900. More recent studies have been reported by Finkelnburg,[2] in which many important aspects of the carbon arc have been analyzed.

The studies to be reported here were made with solid projector-type carbons with anode and cathode of the same size and mounted with their axes in line. It was felt that this arrangement, while in some respects more difficult to work with, would lend itself more readily to analysis. The plan of research was to start at very low currents (1 ampere or less) and gradually increase the current to the hissing stage and beyond. At the same time, it was planned to make simultaneous observations of the variations (hereafter referred to as "oscillations") in voltage, current, light, and sound produced by the arc and correlate the results with those controllable parameters which might lead to a better understanding of the basic processes involved.

EXPERIMENTAL APPARATUS

A DU MONT type *279* dual-beam oscilloscope was used to view simultaneously any two waveforms. The voltage waveforms were projected directly on the oscilloscope and a specially designed noninductive shunt was used to produce the voltage drops corresponding to the current waveforms. Light oscillations were detected by means of a Radio Corporation of America *931-A* phototube and sound oscillations were detected by means of a crystal microphone.

A 24-inch Navy Searchlight Chamber was used to enclose the arc for the studies in air. Average values of voltage and current were recorded on Esterline Angus recording meters.

A General Radio sound analyzer type *760-A*, with range extender as described by Cobine and Curry,[3] was used to measure the frequency of the oscillations up to about 1 megacycle. The measurement of the high-frequency oscillations covering the range above 1 megacycle was made using Hallicrafter superheterodyne radio receivers.

The measurement of arc length was made on an image of the arc magnified optically eight times and projected on a

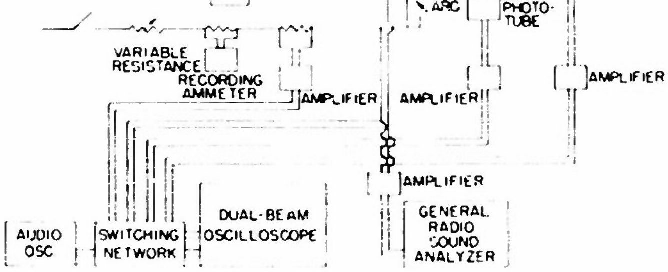

Figure 1. Diagram of apparatus for study of oscillations

Revised text of a conference paper presented at the AIEE Winter General Meeting, New York, N. Y., January 19–23, 1953, and recommended for publication by the AIEE Committee on Electric Welding.

This article is Part I of a series of two articles on self-generated oscillations in the d-c carbon arc. Part II, "The Hissing Arc and Radio-Frequency Oscillations," will appear in a subsequent issue.

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The authors wish to acknowledge the advice and encouragement given them by Dr. W. B. Kouwenhoven, Dean of the School of Engineering, Johns Hopkins University.

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calibrated scale. The arc length was defined as the minimum distance between the anode and cathode.

Power was supplied from a bank of Exide storage batteries capable of supplying 150 amperes at 100 volts for 8 hours. A schematic diagram of the apparatus arrangement is shown in Figure 1.

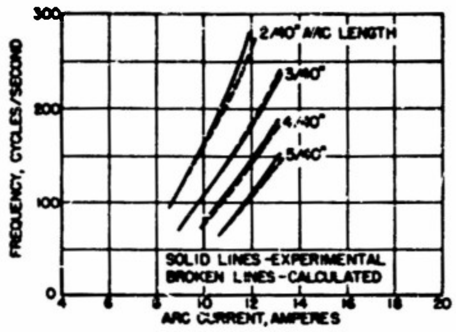


Figure 2. Correlation between measured and calculated values of frequency of quiet oscillations for 3/8-inch electrodes

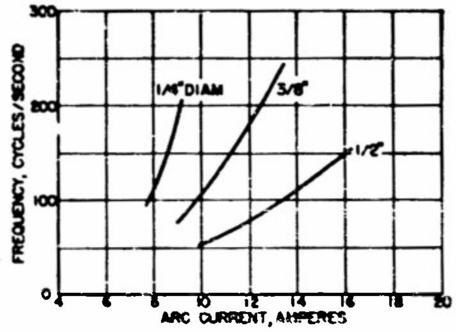


Figure 3. Measured variation of frequency of quiet oscillations with current for 3/40-inch arc length

EXPERIMENTAL RESULTS

With solid carbon electrodes, it was found that if the current was increased slowly from very low values, by varying the external resistance of the circuit, there occurred a critical value of current at which oscillations of voltage, current, light, and sound were produced by the arc. These oscillations occurred at current values just below the hissing point and were of a low frequency, 50–400 cycles. They occurred over a very narrow current range under certain conditions of electrode shape. Since these low-frequency oscillations occurred in the quiet state of the arc, as contrasted with the hissing-state characteristic of higher currents, they were designated as "quiet oscillations," and will be referred to as such hereafter in this article. When the current was increased, the frequency of the quiet oscillations increased until a current was reached at which the arc began to hiss. The low-frequency oscillations then were displaced by the higher-frequency higher-amplitude random fluctuations which are characteristic of the hissing arc.

It was felt that a careful study of the quiet oscillations should be made since an understanding of their mechanism would provide a good groundwork for an analysis of oscillations in the hissing stage and beyond. Consequently, the remainder of this article will present the results of an analysis of the quiet oscillations; the results of studies made on the hissing arc and the high-frequency oscillations associated therewith are scheduled to appear in a subsequent issue.

The quiet oscillations were found to be superimposed on the steady d-c waveforms of current and voltage. The oscillations were of nearly sinusoidal waveform and were smooth and continuous as contrasted to the waveforms of voltage extinctions described by Finkelnburg[2]. The first point of study was to determine if the frequency or occurrence of the oscillations was connected in any way with the inductance or capacitance associated with the external circuits supplying power to the arc. Various values of inductance and capacitance were connected both singly and in combination across the arc, and inductance was connected in series with the arc. None of these reactances affected the oscillations either in frequency, waveform, or any other characteristic.

VOLTAGE OSCILLATIONS

It was found that, for a given size electrode and given arc length, the frequency of the voltage oscillations increased as the current was increased up to the point at which the arc began to hiss. Then the quiet oscillations were no longer observed. The relations between the frequency of the voltage oscillations and the value of arc current for several values of arc length are shown in Figure 2 for electrodes of 9-millimeter (3/8-inch) diameter. Figure 3 shows the relation between oscillation frequency and arc current for an arc length of 3/40 inch and for three different diameter electrodes. It is seen that both electrode size and arc length have an effect on the frequency of the oscillations.

The arc was started in each case with the anode flat as shown in Figure 4*A*. After the arc had burned about 5 minutes at the arc length and current at which measurements were to be made, the electrodes assumed the shape shown in Figure 4*B*. Until the anode had reached the form shown in Figure 4*B*, no oscillations of a stable nature could be obtained. However, after the electrodes reached that shape, the oscillations were relatively stable and the electrodes maintained this shape. The frequency increases as the arc current is increased as shown in Figure 3, but the rate of increase becomes less as the diameter of the electrodes increases. The amplitude of the oscillations increases as the current is increased up to a value of about 3 volts, at which point the arc begins to hiss.

CURRENT OSCILLATIONS

Current oscillations of the same frequency and waveform, but 180 degrees out of phase with the voltage oscillations, were found to be present. A series of photographs of voltage and current oscillations, taken with a Leica 35-millimeter camera from the Du Mont dual-beam oscilloscope, is shown in Figure 5. These oscillations occurred in an arc with 9-millimeter-diameter electrodes, 3/40-inch arc length, and currents ranging from 9 to 12 amperes. The photographs show clearly that there is a 180-degree phase shift between the voltage and current oscillations. This 180-degree phase difference between current and voltage oscillations is to be expected, since the quiet oscillations take place on the negative resistance portion of the voltage-current characteristic of the arc.

Figure 6 shows the approximate variation of arc voltage with arc current for 9-millimeter electrodes and various

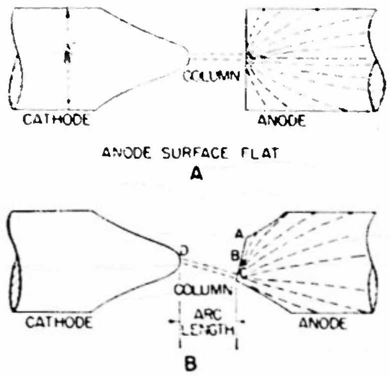


Figure 4. Sketch of anode and cathode showing current flow in anode

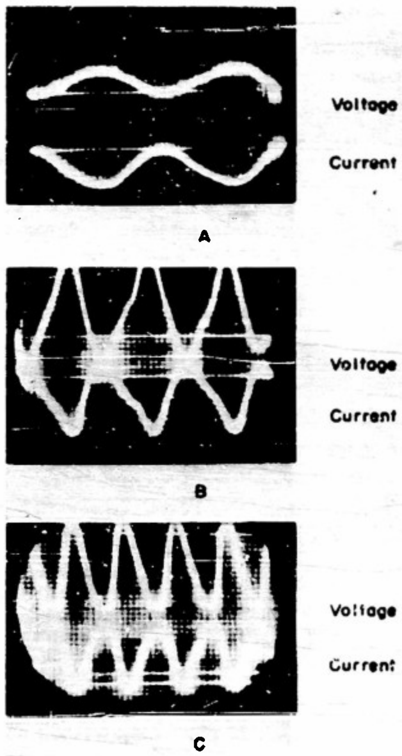


Figure 5. Voltage and current oscillation waveforms for 3/8-inch electrodes, 3/40-inch arc length

values of arc length. The curves show that at low currents, the voltage decreases as the current is increased; that is, that the arc behaves like a negative resistance until a definite current is reached, at which point the arc begins to hiss and the arc voltage abruptly drops 10 volts. A comparison of Figures 2 and 6 shows that the quiet oscillations occur in the current range just below the point at which the arc begins to hiss.

LIGHT OSCILLATIONS

Figure 7 shows typical photographs of the voltage trace (top) and the light trace (bottom) for 9-millimeter electrodes, 3/40-inch arc length, and current about 12 amperes. The three photographs were taken with the same current and arc length, the only difference being the region of the anode from which the light was taken. Figure 7*A* was taken with the phototube aperture focused on the edge of the anode crater at the top looking at the cross section of the arc (point *A* in Figure 4*B*). Figure 7*B* was taken with the aperture focused on the edge of the crater in the middle (point *B* of Figure 4*B*). Figure 7*C* was taken with the aperture focused on the edge of the crater of the bottom (point *C* in Figure 4*B*). In Figure 7*A*, the voltage and light oscillations are almost exactly in phase. In Figure 7*B*, the light lags the voltage about 90 degrees, and in Figure 7*C* the light is 180 degrees out of phase with the voltage. This variation of 180 degrees in phase between the light and the voltage oscillations was observed at all times when the arc was in the quiet-oscillation region, and the light was observed from the bottom of the anode. The reason for this phase shift will be explained later. Figure 8 shows a series of photographs taken at the bottom of the anode crater for the same conditions of electrode size and arc length, but with increasing values of current. Figure 8*D* was taken at a current just below the hissing point. Both the voltage and light waveforms have changed from periodic waves to random variation. At a slightly higher current, the arc begins to hiss, Figure 8*E*. The voltage waveform now appears as a high-frequency hash on the scope while the light oscillations appear as random fluctuations. The amplitude of the hissing voltage measured on the scope was about 10 volts and was independent of the current.

HIGH-SPEED MOTION PICTURES

High-speed motion pictures, 3,000 frames per second, were taken to determine what effects were taking place in the arc during the quiet oscillations. An Eastman Kodak high-speed camera was used with Super *XX* film with an aperture of *f8* and a red filter, Corning number *2418*. The red filter was used to accentuate the effects at the anode surface and suppress the light from the column, which is predominantly blue. The film showed clearly the rotation of a bright spot of light around the outer circumference of the anode crater. A neon timing light built into the high-speed camera was used to provide a 1/120-second timing pulse on the film. The frequency of rotation of the spot thus could be determined. The frequency of rotation was found to be exactly equal to the frequency of the quiet oscillation observed on the oscilloscope at the time the motion pictures were taken.

MECHANISM OF QUIET OSCILLATIONS

Explanation of Observed Results. The high-speed motion pictures show conclusively that there is a connection between the oscillations of voltage, current, light, and sound, and the rotation of the anode spot. A possible cause of the variation in arc voltage would be a variation in arc length as the spot rotates around the anode crater. An analysis of Figure 4*B* shows that such a variation in arc length exists, and that the difference in arc length between top and bottom is the order of 1/64 inch. To determine whether variations in arc length can account for the variations in arc voltage, it is necessary to determine the potential gradient of the column. The potential gradient of the arc column can be determined from the data of Figure 6, and is approximately 160 volts per inch. A variation of 1/64 inch in arc length, therefore, would produce a change of 2.5 volts in arc voltage. This is of the same order of magnitude as obtained from measurements of the voltage oscillations on the dual-beam oscilloscope. Thus, the voltage oscillations appear to be caused by the rotation of the anode spot with a corresponding periodic change in arc length. The current oscillation would follow as a natural result of the changes in voltage and the negative resistance characteristic of the arc.

The 180-degree phase shift of the light oscillations with respect to the voltage across the anode crater now can be explained. Figure 4*B* shows a scale drawing of the electrodes as they appear when the arc is in the quiet-oscillation range. The arc length may be either *DA* when the spot is at the top of the crater, *DC* when it is at the bottom, or any length between these values. As shown in the diagram, *DC* is less than *DA*. Suppose the voltage oscillations are impressed upon one section of the dual-beam oscilloscope and the light oscillations on the other section, and the aperture of the phototube is focused on point *A* of the crater: the voltage then will be a maximum when the anode spot is at point *A*. One-half cycle later, the anode spot will be at point *C*. The voltage and light will be a minimum, since the phototube is still focused on point *A*, while the bright spot of light has moved. Hence, the voltage and light oscillations will be in phase. If the phototube aperture is focused on point *C*, the voltage will be a minimum when the spot is at *C*, but the light will be a maximum. One-half cycle later, when the spot is at *A*, the voltage will be a maximum, and the light will be a minimum. Thus, the voltage and light will be 180 degrees out of phase when the phototube is focused on the bottom of the anode crater and they will be in phase when the phototube is focused on the top of the crater. When the phototube aperture is focused on the middle of the crater, the phase difference will be 90 electrical degrees. This explanation is consistent with Figure 7 which shows the voltage and light in phase at the top of the crater, 90 degrees out of phase in the middle of the crater, and 180 degrees out of phase at the bottom of the crater. The quiet oscillations, therefore, are the result of the rotation of the anode spot around the anode crater.

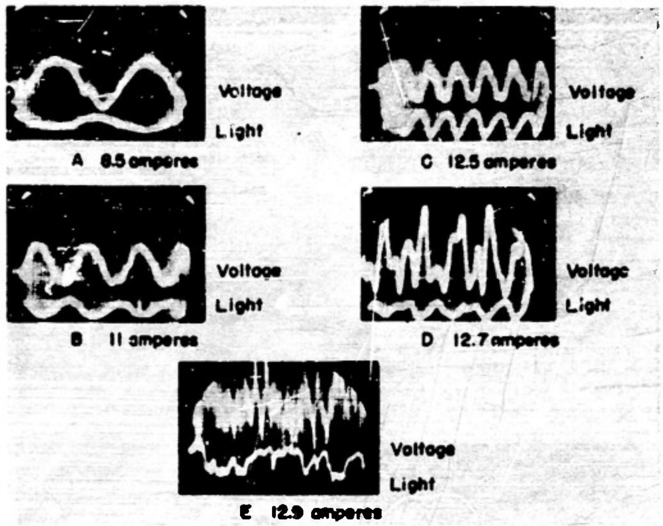


Figure 8. Voltage and light oscillation waveforms, 3/8-inch electrodes, 3/40- inch arc length

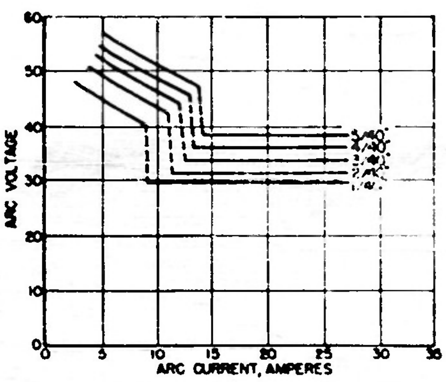


Figure 6. Voltage-current characteristics of carbon arc in air, 3/8-inch electrodes

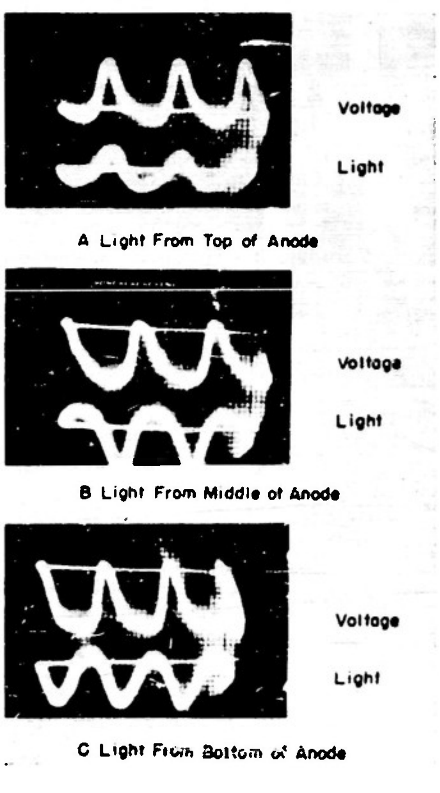
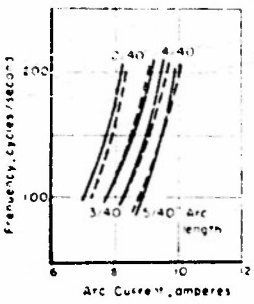


Figure 7. Voltage and light oscillation waveforms for 3/8-inch electrodes, 3/40-inch arc length, 12 amperes

Cause of Rotation. The cause of the rotation is now to be determined. It is known that a beam of electrons in a transverse magnetic field will be acted on by a force which will tend to move it in a direction perpendicular to both the direction of the field and the direction of the beam. Such a motion will be circular. The arc current can be considered to be a concentrated beam of electrons and ions, but mostly electrons. The concentration of electrons is particularly large near the anode. When the current enters the anode spot which is small in comparsion with the anode crater, the current will tend to spread out to form flow lines as shown in Figure 4. Such a distribution of current as in Figure 4 will produce a transverse component of magnetic field at the crater surface. Thus, there will be a tendency for the arc column to rotate. The strength of the magnetic field will depend upon the value of the current and the degree of dissymmetry present at the anode crater. With an electrode which was cut with a perfectly flat face perpendicular to the electrode axis, there would be no transverse component of magnetic field, as in Figure 4*A*. This fact explains why there are no quiet oscillations when the arc is first started with flat electrodes, and why the oscillations become more and more firmly established as the



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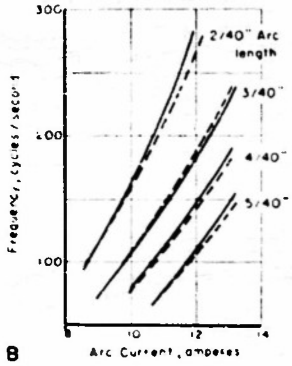
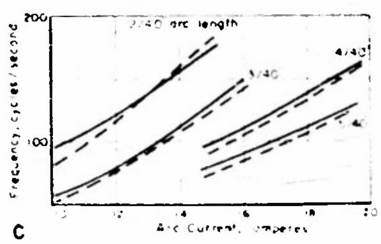


B

Figure 9. Correlation between measured and calculated values of frequency of quiet oscillations. Solid lines—experimental; dotted lines—calculated.

A—1/4-inch electrodes
B—3/8-inch electrodes
C—1/2-inch electrodes



C

electrodes burn so as to attain the final shape. The shape of the anode is the critical factor, and the shape of the cathode tip seems to make no difference. The oscillations will occur with a flat cathode and an anode which has burned to the shape shown in Figure 4*B*. The anode attains this shape as a result of the fact that the heat rises by convection and causes more rapid burning at the top of the electrode.

Effects of External Fields. In order to determine the effects of various types of magnetic fields on the oscillations, several experiments were conducted. The arc was burned in the presence of an external radial magnetic field. When the external field was in such a direction as to aid to the arc's magnetic field, quiet oscillations and hissing occurred at a lower current than without the field. If the magnetic field were reversed so as to oppose the arc's field, quiet oscillations and hissing occurred at a higher current than without the field.

The effect of an axial magnetic field was to increase the amplitude of the quiet oscillations without affecting their frequency. The amplitude of the quiet oscillations increased linearly with magnetic-field strength.

The effect of a transverse magnetic field was to increase the frequency of the quiet oscillations with no effect on the amplitude if the external field were in such a direction as to aid the transverse component of magnetic field produced by the arc. If the external transverse field were reversed, so as to oppose the field produced by the arc, the frequency of oscillation decreased as the field was increased. These studies show clearly that a magnetic field has significant effect on the quiet oscillations and actually can cause them to occur at currents below which they would occur normally. This serves to substantiate the explanation of the cause of the oscillations given previously.

THEORETICAL EXPLANATION OF QUIET OSCILLATIONS

THE DETERMINATION OF an empirical relation between the frequency of oscillation and the arc current was desired. Such a determination can be made by making several assumptions which have been fairly well established in the arc field. Considering that the arc column is essentially a concentrated beam of electrons, such that it can be thought of as a cylinder rotating through the arc atmosphere, the following equation was developed:

$$f = CI^{n+1}/Rrl_2$$

where C and n are constants depending upon the electrode diameter; I is the arc current in amperes; R is the radius of the arc column; r is the radius of rotation of the anode spot; and l_2 is the arc length.

The comparison between the measured values of the frequencies of the quiet oscillations and the calculated values from this empirical equation are shown in Figure 9, for three sizes of electrodes.

Tests With Other Types of Electrodes. Attempts were made to obtain quiet oscillations with electrodes other than the National Carbon Company solid projector carbons used in all the work thus far reported. No other electrode produced oscillations as stable as those with carbon. Graphite electrodes produced hissing with no noticeable region of quiet oscillation before hissing began. Copper, aluminum, and tungsten electrodes showed a region of voltage fluctuation before hissing began, but there were no stable oscillations that could be studied as in the case of carbon.

CONCLUSIONS

THE RESULTS of this research may be summarized as follows:

1. A study of the d-c arc in air at normal temperatures and pressures between solid carbon electrodes has disclosed the presence of symmetrical, uniform oscillations of current, voltage, light, and sound occurring at current values just below the hissing stage.

2. The oscillations are of low frequency in the range 50 to 400 cycles.

3. The oscillations occur with high uniformity only after the anode tip has attained its characteristic shape.

4. The frequency of the oscillations is affected by the material, diameter, and separation of the electrodes and by the arc current, but not by reactance present in the power supply.

5. The oscillations are caused by rotation of the anode spot about the periphery of the anode due to the presence of an unsymmetrical magnetic field caused by the arc current itself at the anode surface.

6. An empirical equation has been developed to express the frequency of the oscillations as a function of current and electrode parameters.

7. It is believed that the behavior of the anode spot and the influence of the arc's own magnetic field as reported here have a direct bearing on the initiation of the "hissing" arc and on its characteristics.

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Attention: Metallurgy Panel

Dear Sir:

Enclosed herewith are ~~two (2)~~ one (1) copies of Technical Report No. 3 "A Study of Fundamental Processes Causing Instability in D-C Arcs" in connection with our work on Contract Nonr 248(09). This report completes our studies of the oscillations in direct current arcs which were found to be caused by motion of the anode spot in the arcs own magnetic field. These oscillations are believed to be one of the major causes of instability in the operation of the high current arc.

Our studies of arc stability have resulted in the publication of three papers by the American Institute of Electrical Engineers and the work has been presented orally at two National Technical Conferences. A reprint of one of these papers forms a part of the enclosed Technical report. It is felt that the results have provided a contribution to the knowledge of the fundamental processes taking place in electric arcs and as such should be of help to those who are designing apparatus and procedures in which the arc is employed.

As noted in our last Status report, our program of basic arc research is being continued with emphasis on the effects of various combinations of electrode materials and of mixtures of the inert gases on the behavior of the high current arc. A paper describing some of the results of this work has been submitted for publication to the American Institute of Electrical Engineers.

Copies of the enclosed report are being mailed in accordance with the attached Distribution List.

Very truly yours,

T. Benjamin Jones

T. Benjamin Jones
Research Contract Director

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Bureau of Aeronautics
Navy Department
Washington 25, D. C.
Attn: N.E.Promisel, AE-41 (3)
Technical Library, TD-41 (1)

Commanding Officer
Naval Air Material Center
Naval Base Station
Philadelphia, Pa.
Attn: Aeronautical Materials Lab. (1)

Bureau of Ordnance
Navy Department
Washington 25, D. C.
Attn: Rex (3)
Technical Library, Ad3 (1)

Superintendent, Naval Gun Factory
Washington 20, D. C.
Attn: Metallurgical Lab., In 910 (1)

Commanding Officer
U.S. Naval Ordnance Laboratory
White Oaks, Maryland (1)

Commanding Officer
U.S. Naval Ordnance Test Station
Inyokern, California (1)

Bureau of Ships
Navy Department
Washington 25, D.C.
Attn: Code 343 (3)
Code 337L, Technical Library (1)

U. S. Naval Engineering Experiment Station
Annapolis, Maryland
Attn: Metals Laboratory (1)

Director, Materials Laboratory
Building 291
New York Naval Shipyard
Brooklyn 1, New York
Attn: Code 907 (1)

NAVY

Chief, Bureau of Yards and Docks
Navy Department
Washington 25, D. C.
Attn: Research & Standards Div. (1)

Post Graduate School
Monterey, California
attn: Department of Metallurgy (1)

ARMY

Chief of Staff, Department of the Army
The Pentagon
Washington 25, D. C.
Attn: Director of Research & Development (1)

Office of Chief of Ordanance
Research and Development Service
Department of the Army
The Pentagon
Washington 25, D. C.
Attn: ORDTB-Research Coordination Branch (3)

Commanding Officer
Watertown Arsenal
Watertown, Massachusetts
Attn: Laboratory Division (1)

Commanding Officer
Frankford Arsenal
Philadelphia, Pa.
Attn: Laboratory Division (1)

Office of the Chief of Engineers
Department of the Army
The Pentagon
Washington 25, D.C.
Attn: Research and Development Branch (1)

AIR FORCES

U. S. Air Forces
Research and Development Division
The Pentagon
Washington 25, D.C. (1)

AIR FORCES

Air Material Command
Wright-Patterson Air Force Base
Dayton, Ohio
Attn: Materials Laboratory
MCREXM (2)

OTHER GOVERNMENT AGENCIES

U. S. Atomic Energy Commission
Division of Research
Metallurgical Branch
Washington 25, D.C. (1)

National Bureau of Standards
Washington 25, D.C.
Attn: Physical Metallurgy Division (1)

National Advisory Committee for Aeronautics
1724 F Street, N.W.
Washington 25, D.C. (1)

Research and Development Board
Committee on Basic Physical Sciences
The Pentagon
Washington 25, D.C.
Attn: Metallurgy Panel (1)

Chief of Bureau of Ships
Navy Department
Washington 25, D.C.
Attn: Code 692 (1)

Operations Evaluation Group
Chief of Naval Operations
Navy Department
Washington 25, D.C.
Attn: E.S. Lamar (1)

W. Spraragen, Director
Welding Research Council
29 W. 39th Street
New York 18, New York (1)

Armour Research Foundation
Metals Research Laboratory
Technology Center
Chicago 16, Illinois
Attn: Dr. J. M. Parks (1)

Mr. James F. Lincoln
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Westinghouse Research Laboratories
East Pittsburgh, Pennsylvania
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Research Laboratories
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Engineering Research Laboratories
Engineer Center
Fort Belvoir, Virginia (1)

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